UNIVERSIDADE FEDERAL DE SANTA CATARINA
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Estevan Hideki Murai

PROJETO DE MECANISMOS DE COSTURA COM ACESSO UNILATERAL USANDO SÍNTESE DO NÚMERO E DO TIPO

Florianópolis

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Dissertação submetida ao Programa de Pós-Graduação em Engenharia Mecânica para a obtenção do Grau de Mestre em Engenharia Mecânica.
Orientador: Daniel Martins, Dr. Eng.
Coorientador: Henrique Simas, Dr. Eng.

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Esta Dissertação foi julgada aprovada para a obtenção do Título de "Mestre em Engenharia Mecânica", e aprovada em sua forma final pelo Programa de Pós-Graduação em Engenharia Mecânica.

Florianópolis, 8 de Agosto 2013.

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Este trabalho é dedicado à minha família, meus amigos e a todos aqueles que me apoiaram na minha trajetória até aqui.

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The good thing about science is that it's true whether or not you believe in it.

Neil deGrasse Tyson

RESUMO

O projeto de novos dispositivos mecânicos depende da experiência e conhecimento do projetista. Metodologias de projeto foram desenvolvidas visando diminuir essa dependência. Neste trabalho, algumas metodologias de projeto de mecanismos são analisadas e comparadas. Em seguida, uma nova metodologia é proposta, com foco na determinação das características estruturais e no uso dos requisitos de projeto para eliminar mecanismos inviáveis. Outro objetivo da metodologia proposta é sistematizar o projeto de mecanismos de modo a reduzir decisões subjetivas por parte do projetista. Por fim, a metodologia proposta é aplicada no projeto de mecanismos de costura.
Os mecanismos de costura podem ser classificados em dois tipos: com acesso bilateral e com acesso unilateral. A costura com acesso unilateral apresenta grande potencial para diversas aplicações, tanto na indústria têxtil quanto em áreas menos tradicionais, como a medicina. Entretanto, poucos dispositivos para a costura com acesso unilateral foram desenvolvidos com sucesso. Neste trabalho, o mecanismo de costura projetado é do tipo com acesso unilateral.
O desenvolvimento do projeto segue a metodologia proposta. Assim, faz-se inicialmente um levantamento do estado da arte de mecanismos de costura com acesso unilateral. Utilizando o levantamento do estado da arte, listam-se os requisitos necessários para tal mecanismo. Em seguida, faz-se a síntese de mecanismos de costura com acesso unilateral. Após a eliminação de mecanismos inviáveis, apresentam-se dois mecanismos de costura com acesso unilateral. Finalmente, notou-se que a metodologia utilizada tornou o projeto independente do projetista visto que nenhuma decisão foi subjetiva.

Palavras-chave: Costura com acesso unilateral. Dispositivos de costura. Síntese de mecanismos. Metodologia de projeto de mecanismos.

ABSTRACT

The design of new mechanical devices depends on the designer's experience and knowledge. Design methodologies were created in an effort to make the design process less dependent on the designer. In this work, a few mechanisms design methodologies are analysed and compared. Then, a new methodology is proposed, concentrating on the determination of structural characteristics and on the use of the design requirements to eliminate unfeasible mechanisms. Another objective of the proposed methodology is to systemise the design of mechanisms in order to reduce subjectives decisions from the designer. The proposed methodology is then applied to the design of stitching mechanisms.

Stitching mechanisms can be classified in two types: two-side access and one-side access. Stitching with one-side access has a great potential for many applications, such as textile industries or even medicine; although, few of such designed devices were successfully developed. In this work, the stitching mechanism designed is with one-side access.

The development of the mechanism follows the proposed methodology. Initially, a state of the art survey for one-side stitching devices is carried out. Once the survey is done, all design and structural requirements for an one-side stitching device are listed. Then, the synthesis of mechanisms for a one-side stitching device is done. After unfeasible mechanisms are eliminated, two solutions for stitching devices with one-side access are presented. Finally, the proposed methodology made the design process independent from the designer since no subjective decision was taken.

Keywords: One-side stitch. Stitching devices. Mechanism synthesis. Mechanisms design methodology.

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LIST OF ABBREVIATIONS

1-SSD	One-side stitching device
2-SSD	Two-side stitching device
CAD	Computer-aided design
DOF	Degrees of Freedom
IFToMM	International Federation for the Promotion of Mechanism and Machine Science

LIST OF SYMBOLS

C_{ij}	Connectivity between links i and j
e	Number of elements of kinematic pair
f_i	Degree of freedom of pair i
j	Number of pairs with one degree of freedom
K_{ij}	Degree of control between links i and j
M	Mobility of the kinematic chain
M'	Mobility of a subchain in a kinematic chain
n	Number of links
R_{ij}	Redundancy between links i and j
V	Variety of the kinematic chain
λ	Order of the screw system
ν	Number of independent loops

CONTENTS

1 INTRODUCTION

This dissertation analyses a few mechanism design methodologies and proposes a new methodology. The proposed methodology systematises the design of mechanisms, focusing on deciding the structural and design requirements. Once the methodology is presented, it is applied to synthesise a stitching device. Finally, two innovative stitching mechanisms are presented.

1.1 MECHANISM DESIGN METHODOLOGIES

Nowadays, a great effort has been done to design faster and to create better and more innovative products. To accomplish that, several design methodologies were developed, including the field of mechanism design.

Yan (1999) emphasises the value of a methodology for designing. “A design process is a logical sequence of events to ensure the success of designing devices, products, systems, or processes”(YAN, 1999, p. 14). Therefore, the design of a new device, product, system or process must start by selecting an appropriated methodology.

A great contribution to mechanism design methodologies was made by Hartenberg and Denavit (1964). In this methodology, the process of developing a mechanical device is divided in three steps: number synthesis, type synthesis and dimensional synthesis. Number synthesis studies how the links are connected to each other and how this affects the kinematic chain’s mobility. Type synthesis determines the motion type allowed by the kinematic pairs. Finally, dimensional synthesis sets the size of the links and angles of the points of interest.

The three basic steps of Hartenberg and Denavit (1964) are presented in all other methodologies. Depending on the methodology, such steps may be combined, occur simultaneously or appear in a different order; nevertheless, understanding the steps presented in Hartenberg and Denavit (1964) is important to understand third party methodologies.

Among the most recent mechanism design methodologies, there are those by Yan (1999) and Tsai (2000). The approaches in these methodologies are more focused on graph theory (used during the number synthesis step) and combinatorial analysis (used in both number and type syntheses step).

In addition to the three steps of Hartenberg and Denavit (1964), the methodology proposed by Yan (1999) includes a state of the art survey. The objective of this survey is to analyse existing projects which tasks are similar to the desired task. These projects’ structural characteristics are used in the number synthesis step. Finally, Yan's methodology results in several possible designs, which must be compared to the existing designs to identify the innovative solutions.

The methodology proposed by Tsai (2000) is wider than the previously presented. Compared to Yan's methodology, Tsai's methodology has steps considering design optimization, computer simulation, prototype demonstration, documentation and production phase.

Such methodologies can be applied to the problem of sewing with one-side access in order to develop a sewing device capable of sewing, accessing only one side.

1.2 STITCHING MECHANISMS

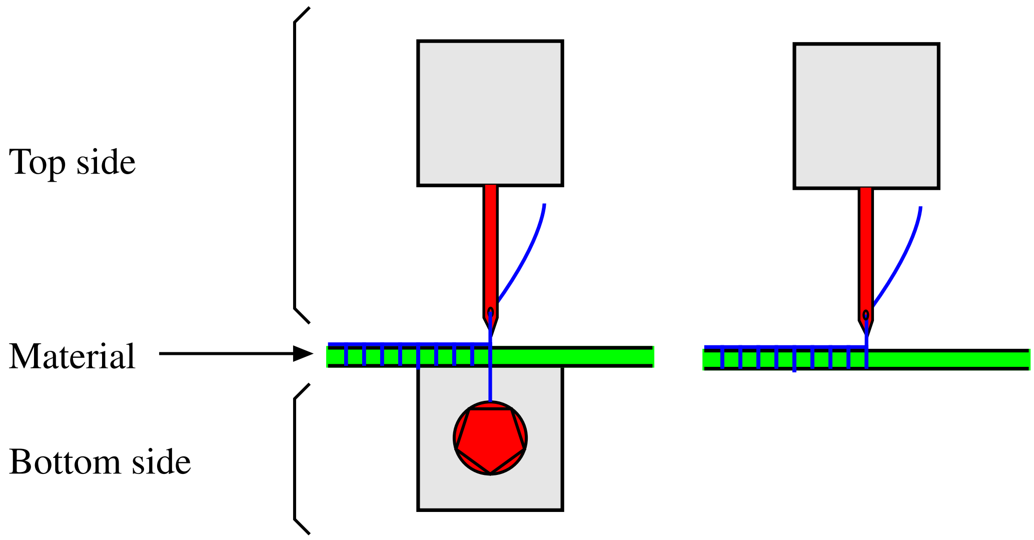
Although "sewing machine" is a common term used daily, in the technical field of stitching is more usual to refer to such machines as "stitching machines". The verb "to sew" is also replaced with "to stitch". This terminology is defined by standard ISO-4915 (1991) and is also used in standard ASTM-D6193 (1997). The Brazilian standard for types of stitches, NBR-13483 (1995), is based on ISO-4915 (1991), however, as NBR-13483 (1995) is written in Portuguese, this work will use the terminology defined by ISO-4915 (1991) since ISO-4915 (1991) is written in English.

The stitching machine function is to join two or more parts using threads. It notices that there is a wide range of materials that can be stitched together and many different types of seam and materials for the thread. Therefore, there are many situations where a seam can be used (UDAKHE; BASUK, 2011).

Compared to screws, nails and staples, the seam is cheaper and lighter. Also, it allows the stitched surface to bend, which may be desirable in situations as clothing, closing tubular tyres, constructing flexible ducts or attaching the sheets of a book together. Another advantage is that the seam can be continuous, which results in a more uniform strength along the joint and in some sealing capabilities.

1.2.1 Two-side and one-side stitching devices

A stitching device can be classified in two types: two-side and one-side. In a two-side stitching device (2-SSD), the components may be under and above the material that is being stitched. A general example of a 2-SSD is shown in Figure 1a. In a one-side stitching device (1-SSD), all components are on the same side, in relation to the material that is being stitched. An example of a 1-SSD is shown in Figure 1b.



(a) Two-side stitching device. (b) One-side stitching device.

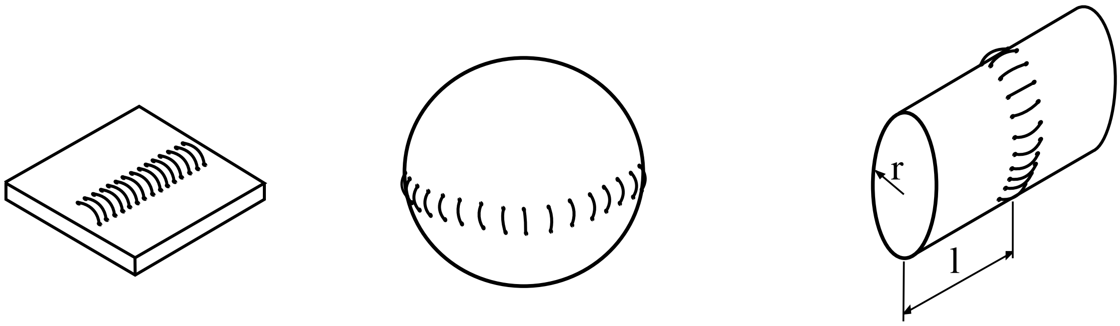
Figure 1: Example of a two-side stitching device and a one-side stitching device.

2-SSDs are more developed and far more usual than 1-SSDs, since 2-SSDs can perform more types of stitches and the field of application is larger than those of 1-SSDs. However, some situations require a 1-SSD, as will be exposed in Section 1.3.

A seam on a closed surface (see Figure 2b) is only possible by using a 1-SSD. Although, theoretically, all open surfaces (see Figure 2a) can be stitched using a 2-SSD, in some cases it is unpractical to do so. In these cases a 1-SSD is desired and they will be explored in the next section.

1.3 APPLICATIONS OF ONE-SIDE STITCHING DEVICES

A 1-SSD can stitch closed surfaces, open surfaces and almost-closed surfaces. An almost-closed surface is an open surface which is difficult to stitch using a 2-SSD because of the surface's high slenderness ratio. Such slenderness ratio is defined as a length divided by an area. The length is measured by the seam depth related to the open side used to insert the stitching device. The area is the cross section area of the cited open side. In the case of an almost closed cylindrical surface, as exposed in Figure 2c, the slenderness ratio is $l/\pi.r^2$.



(a) Open surface. (b) Closed surface. (c) Almost closed surface.

Figure 2: Types of stitching surfaces.

Stitching an elbow patch after the sleeve is done is an example of stitching an almost-closed surface. In this case, the 2-SSD shape must allow one side of the stitching device to enter inside the sleeve. Therefore, with the garment being between the bottom and the top parts of the stitching device, the patch can be stitched.

However, when the sleeve's slenderness ratio is high, the slenderness ratio of one part of the stitching machine must also be high. In addition, the slenderer the sleeve, the more confined the workspace inside the surface will be. This constraint reduces garment mobility in relation to the stitching machine. Since stitching machines usually stitch only in one direction, the garment orientation must be adjusted to stitch in the desired direction. Thus, the lack of mobility can make the stitching process harder or impossible.

As a 1-SSD does not need access to both sides, it can be small enough to stitch from the inside. It could also be used to stitch from the outside, avoiding any slenderness problem. Therefore, considering just the types of stitches that a 1-SSD can perform, the application limits for a 1-SSD are wider than those for the 2-SSD (SRIKRISHNAN; PARTHIBAN; VIJU, 2011).

1.3.1 Industry applications

Industry applications for a 1-SSD are those in which the manufactured products require seam, but given the product geometry, it is desirable to stitch with a 1-SSD. Example of such products are: tubular tyres, flexible ducts and industrial filters (BROWN, 2007; SOLENT, 2013). General textile industries products are also examples of applications and a 1-SSD can be used in this area to optimise a manufacturing process.

1.3.1.1 Adding more flexibility to manufacturing lines

One-side stitching devices can be used to add more flexibility in a manufacturing line.

Considering the example of a small shirt manufacturing, such as baby clothes. If the longitudinal seam (along the sleeve) is stitched first, see Figure 3, then the hem must be stitched in a machine with one side small enough to enter inside the sleeve. As mentioned in Section 1.3, it might be impossible to stitch the hem, given the slenderness ratio. A solution is to stitch the hem first, and then make the longitudinal seam. Therefore, the order of the seams must allow to successfully finish the shirt.

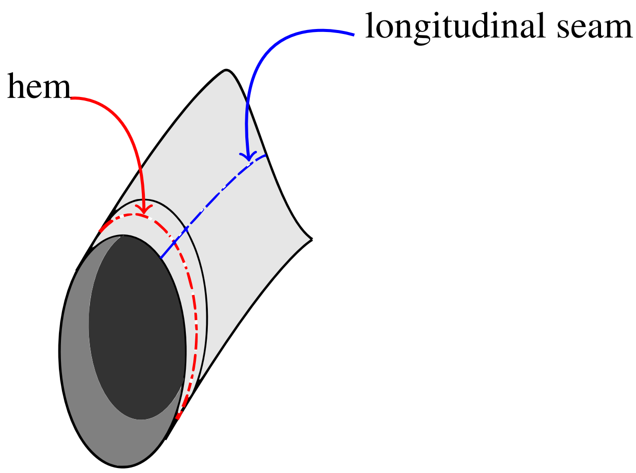


Figure 3: Longitudinal seam and hem of a sleeve.

If several workstations are used, their layout must consider the order in which the seams are done. In the layout and process optimisation problem, a fixed order for the seams implies more constraints. These additional constraints can reduce the number of feasible solutions and, possibly, eliminate good solutions.

A 1-SSD would make the order for the seams more flexible, thus, adding more flexibility to manufacturing lines.

1.3.1.2 Stitching layers of a composite material

The use of composite materials is increasing in high technological fields. Although the mechanical properties of these materials are remarkable, the process of shaping them into the desired form is a laborious task. Modern techniques were developed to facilitate this process and among them are stitching techniques.

Stitch-based techniques have the advantage of being a quick, simple and low cost process (ZHAO et al., 2009). In addition, it is easy to be automated and it enhances the mechanical properties of the composite.

It is important that the stitching device be a 1-SSD to stitch complex forms and not only flat profiles (BRANDT; DRECHSLER; FILSINGER, 2001; WITTIG, 2001). These techniques use a 1-SSD fixed to a robot arm to stitch the layers together, thus, many complex forms can be stitched.

1.3.2 Applications in medicine

Another field of application for a 1-SSD is medicine, using it with minimally invasive techniques.

The purpose of minimally invasive techniques is to perform the necessary medical procedures but reducing as much as possible the damage to the patient's body. Accordingly, the recover time, infection probability, loss of blood and mortality rate are reduced (SAADI et al., 2006). Furthermore, an aesthetic advantage is that the scars are reduced.

Endoluminal surgeries are minimally invasive procedures that use the human body's empty internal volumes in medical procedures. Such volumes are called lumens. Examples of lumens are the esophagus, stomach, intestines, bladder, arteries and veins. Many breakthroughs have been done lately in this field, not only in techniques but also in materials and tools (VERDONCK, 2008).

Typically, an endoluminal surgery would start with a small incision to access a lumen. Then, the catheter containing the tool and material required by the surgery is inserted in the lumen. More than one incision can be done in order to use several catheters. These catheters are inserted until they reach the surgery location. Once the surgery is done, the catheters are removed and the incisions are stitched.

In a conventional surgery, the incision size would be significantly larger. This incision needs to be large enough to allow the handling of conventional tools and application of conventional methods; therefore, exposing the patient to additional risks. A comparison between both methods is shown in Figure 4, in which the left and centre images show endoluminal procedure and the right shows the conventional procedure.

Endoluminal surgeries are characterised by having access to only one lumen side. Therefore, if the medical procedure demands a suture, a 1-SSD will be needed. There is a need for a universal tool that can suture in endoluminal surgeries (VERDONCK, 2008).

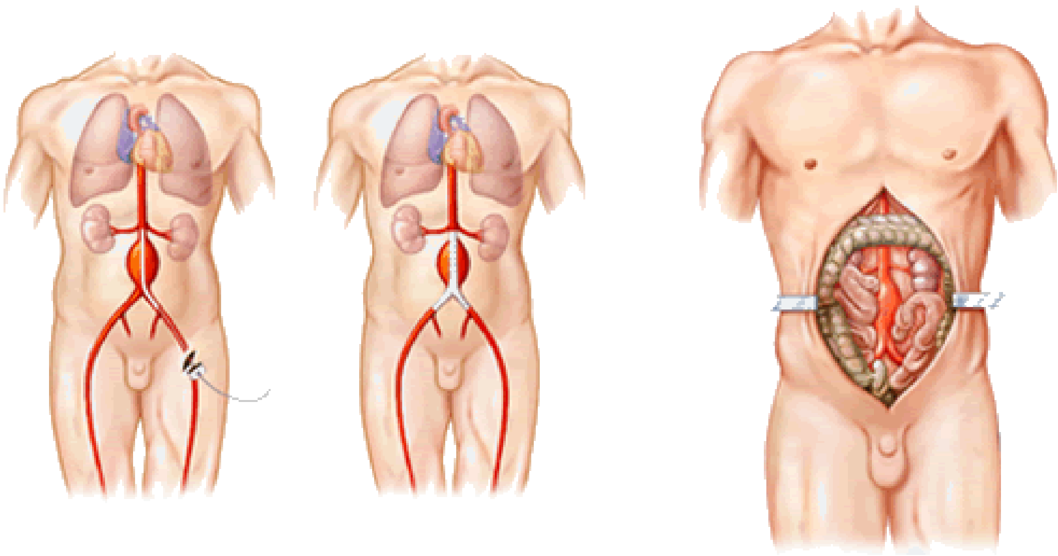


Figure 4: Comparison between endoluminal and conventional surgery. Adapted from SITE (2011).

1.3.2.1 Abdominal aortic aneurysm repair

An example of endoluminal surgery is endovascular repair of abdominal aortic aneurysms. An arterial aneurysm is defined as a dilatation of 50 % or more of the diameter of an artery (RAMPINELLI, 2000). Such dilatation can occur because of artery impairment associated with blood pressure.

This vascular deformation can occur locally, resulting in a saccular aneurysm or along the artery, resulting in a fusiform aneurysm. Both types of aneurysm are exposed in Figure 5, in which the left is the saccular and the right is the fusiform.

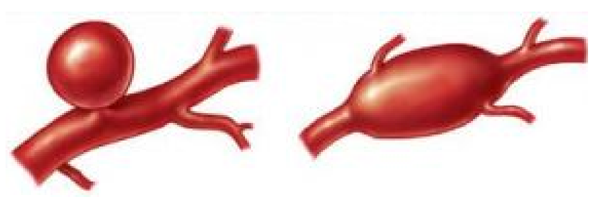


Figure 5: Saccular and fusiform aneurism. Adapted from Raupp (2011).

Unless treated, the aneurysm may rupture, which will cause an internal bleeding that can result in death. The treatment types are conventional or endoluminal surgery. The minimally invasive procedures use the stent-graft.

The stent-graft is an endoprothesis that is inserted inside the artery, at the aneurysm location. Its function is to stop the blood from flowing into the aneurysm, relieving the pressure inside of it. The stent-graft is composed by a metallic structure (stent) and a polymeric covering (graft). It can be compacted to fit inside a catheter but, when it is without any restriction, the stent will expand as a spring, opening the graft.

The stent pressure on the vascular wall generates a friction force that holds the stent-graft in position. In addition to the frictional force, there may be hooks that help the stent-graft to secure to the vascular wall. The procedure to implant the stent-graft is shown in Figure 6.

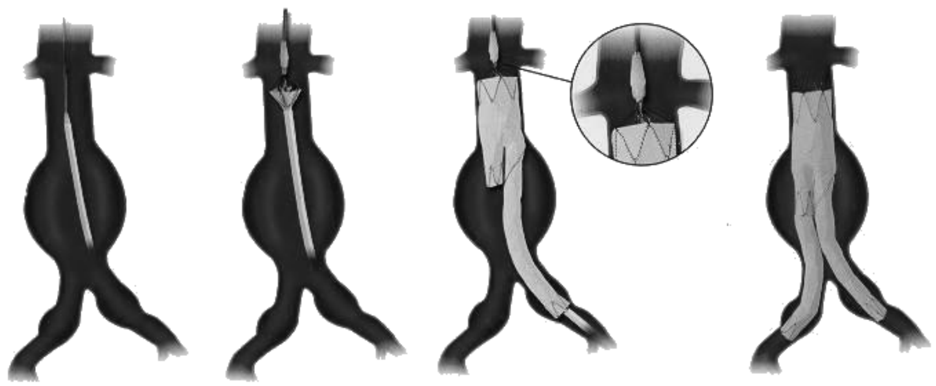


Figure 6: Placement of a stent-graft. Adapted from Biasi (2001).

However, in some cases the stent pressure against the vascular wall may not be sufficient to prevent blood from flowing into the aneurysm. Furthermore, it is possible that the stent-graft moves after the surgery. In these cases it is necessary an intervention.

Another drawback is the incompatibility of the stent's metal with blood. When in contact with metal, blood coagulates and can lead to a thrombosis. To reduce the coagulation, the patient needs to be constantly medicated with anticoagulant (VERDONCK, 2008).

A 1-SSD could be used to attach the graft to the vascular walls. This could eliminate the stent use and reduce the chances of the graft to move. In addition, it could decrease the probability of blood flowing into the aneurysm persists after the procedure.

Moreover, without the stent, the coagulation could be reduced. Therefore, the use of medicines could be shortened.

Finally, the replacement of the stent with a seam would reduce the surgery cost, since the stent is more expensive to manufacture than the suture thread.

1.4 WORK PURPOSES

The purpose of this work is to contribute to the field of mechanisms design. Such contribution is made by analysing existing mechanism design methodologies and proposing a more systematised methodology. Once the new methodology is presented, an example of its application is given, synthesising a 1-SSD.

Other purpose of this work is to study 1-SSDs and to synthesise an innovative mechanism to perform stitches with one-side access. The specific goals inside this purpose is to make the number and type syntheses of a 1-SSD. During this designing process, tools developed or implemented by the Robotics Laboratory of Federal University of Santa Catarina are used.

1.5 WORK DELIMITATIONS

A limit for this work is due to its wide possibilities of application, as it was exposed in Section 1.4.

For example, a 1-SSD focusing on adding flexibility to a manufacturing line (Section 1.3.1.1) would require high speed and repeatability, among others characteristics. To accomplish that, the joints would need to have low friction and high precision. If the application has to stitch composites materials (1.3.1.2), then hardiness is more important than speed. Therefore, the joints must be robust. In case of a medical application (Section 1.3.2), miniaturization and asepsis are important, hence, the selected materials must be aseptic. In addition, the joints physical realisation and the links dimensions must be small while preserving its functions.

Therefore, the kinematic pair physical realisation, dimensional synthesis, choice of materials and other aspects of the design process are left to be made according to the 1-SSD application.

1.6 JUSTIFICATION

There are many applications for a 1-SSD. Although Section 1.3 only exposed a few, those presented applications are unexpected in a first thought about the topic. Since it is up to the designer to analyse both conservative and innovative solutions for the problem, there could be many unforeseen uses for a 1-SSD.

While 1-SSDs present great opportunity for innovation in industry and research, their designs remain under-study if compared to 2-SSDs. As will be exposed in Section 3.2, the quantity of 1-SSD designs or patents are relatively low and, so far, no device has become a successful commercial product.

1.7 OVERVIEW OF THIS WORK

This work is organised into five chapters and two appendices.

Chapter 1 is an introduction to mechanism design methodologies and to the problem of stitching with one-side access. This chapter also presents several applications for a 1-SSD. The objectives and limitations of this work are also presented.

Chapter 2 presents a brief review on mechanism design methodologies. Then, a new methodology for mechanism design is proposed. Chapter two also presents a basic review on number and type syntheses, it focuses on how to use the design and structural requirements to assist the designer to identify the most promising mechanisms.

Chapter 3 presents a state of the art survey on 1-SSDs. Such survey is used to understand the problem of stitching with one-side access and to analyse the existing solutions for this problem. Then, based on the informations collected in the survey, structural and design requirements are listed.

Chapter 4 uses a group of three structural characteristics to make the number synthesis, enumerating all kinematic chains and then mechanisms with such characteristics. The requirements are used to identify the unfeasible chains and mechanisms so they can be discarded. Then, the types of pairs available are listed and type synthesis is done. The result is analysed and unfeasible mechanisms are discarded. Two possible mechanisms for 1-SSD are found.

Chapter 5 presents the conclusions and topics for further works.

Appendix A presents the analysis of feasibility for a list of mechanisms enumerated with a group of structural characteristics different from those used in chapter four.

Appendix B presents the user interface developed for the software of synthesis and analysis of kinematic chains and mechanisms.

2 BIBLIOGRAPHIC REVIEW AND PROPOSED METHODOLOGY

This chapter presents a new methodology and the theoretical tools used in this work. First, basic concepts of mechanisms are presented. Then, a bibliography review on mechanism design methodologies is exposed. Three methodologies are presented and their characteristics are listed. Based on that, a new methodology is proposed, which is used in this work. Then, each main step of the methodology is detailed and the necessary tools for these steps are presented, with focus on the selection of a mechanism.

2.1 CONCEPTS OF MECHANISMS THEORY

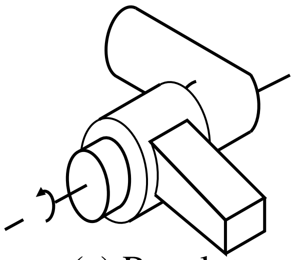
In this section it is exposed a review on concepts of mechanisms theory. The terminology exposed here is in accordance with the International Federation for the Promotion of Mechanism and Machine Science (IFToMM). For further information about terminology, see Ionescu (2003), Tsai (1999) and Hunt (1978).

A body is considered rigid if any two points on it do not have a relative movement to each other, *i.e.*, the body does not deform. Although no such body exists, in some cases a body can be considered as rigid since this approximation is precise enough and it simplifies the system's mathematical model. The mechanism's bodies are called *links*, and, generally, they can be considered as rigid bodies (TSAI, 1999).

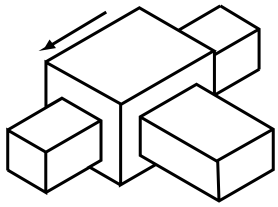
A link with no connections can move freely in space by translations, rotations or any combination of those motions. Such link has six *degrees of freedom* (DOF). Hence, the DOF is the number of independent variables necessary to fully determine the configuration of a system. The DOF between two links can be reduced by connecting them, imposing restriction to their relative motions. Links can be classified according to the total of these connections. A binary link is connected to two other links, a ternary to three other, and so on. These connections between bodies are called kinematic pairs. A link connected to three or more links is called a *polygonal link*.

A *kinematic pair* is formed by a connection between two parts called *elements of kinematic pair* (or, by context, just elements). A kinematic pair (or just pair) can reduce the DOF between two links. This reduction is determined by the interaction of the surfaces, lines or points of the elements, resulting in different types of pairs.

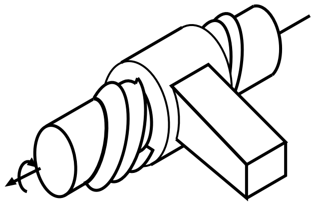
Kinematic pairs can be classified in lower and higher pairs (HUNT, 1978). Lower pairs have their elements connected by surfaces while higher pairs elements are connected by lines or points. The lower pairs are shown in Figure 7 and two examples of higher pairs are exposed in Figure 8.



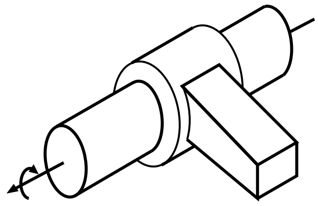
(a) Revolute pair.



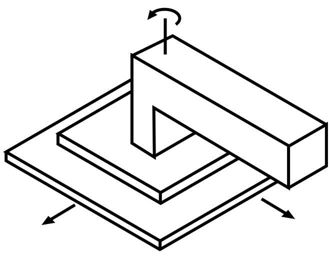
(b) Prismatic pair.



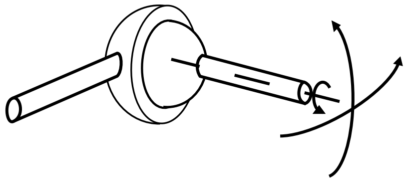
(c) Helical pair.



(d) Cylindric pair.



(e) Planar pair.



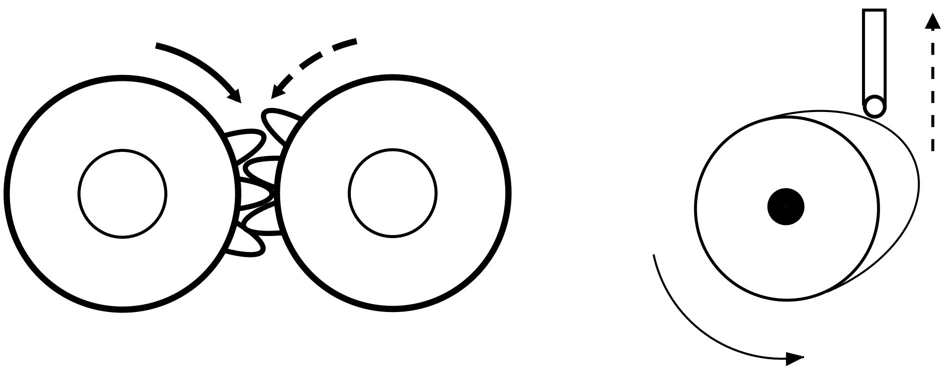
(f) Spheric pair.

Figure 7: Lower kinematic pairs.

In addition, a kinematic pair with i DOF (which freedom is f_i) can be replaced with i pairs with a single DOF. For example, the cylindric pair from Figure 7d has two DOF, one translational and one rotational. Thus, it can be replaced with two pairs, one revolute and one prismatic. Such substitution is called *expansion of kinematic pair*. It notices that to maintain the cylindrical motion, the revolute pairs' rotation axis must be parallel with the prismatic pair's translation axis. The opposite replacement is also valid, *i.e.*, substitute i f_1 pairs with one f_i pair. Such substitution is called *contraction of kinematic pair*.

A *joint* is a kinematic pair physical realisation. For example, a revolute pair may have many different realisations, such as journal bearing or rolling bearing.

A joint can have an apparatus attached to it, that will cause relative motion between that joint's links in response to a given signal. Such apparatus



(a) Gear pair.

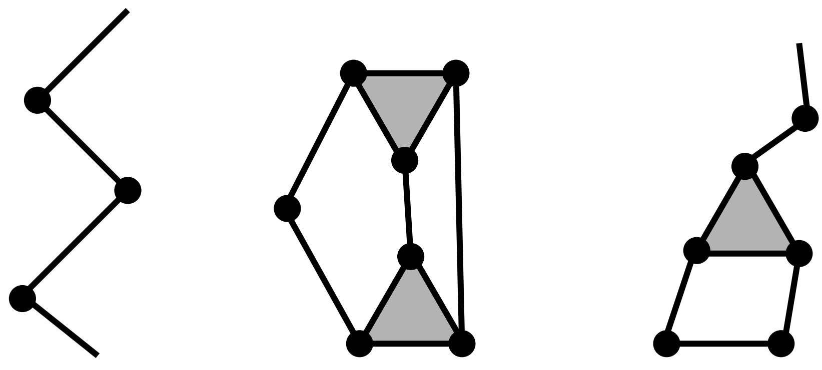
(b) Cam pair.

Figure 8: Higher kinematic pairs.

is called *actuator*.

An assembly of links and pairs is called a *kinematic chain* (or *chain*). When a subset of links on a kinematic chain forms a closed circuit, such subset is called *loop*.

A kinematic chain can be classified in open, closed and hybrid. A kinematic chain is considered open if there is only one possible sequence of links and kinematic pairs connecting any two links; an example is shown in Figure 9. A closed chain has at least two distinct sequences of links and kinematic pair connecting any two links. A chain is hybrid if it has both open and closed parts.



(a) (b) (c)

Figure 9: Types of kinematic chains. (a) Open chain. (b) Closed chain. (c) Hybrid chain.

A sequence of links and kinematic pairs in a kinematic chain is called a *subchain*.

The set of links that belongs to a kinematic chain is called *partition*.

A *mechanism* is a kinematic chain with one link as a frame, which is called the fixed-link.

A *device* is a machine or machine's component that performs one or more simple tasks.

The term *kinematic structure* has been used recently to refer to all characteristics of the kinematic chain, that do not depend on the dimensions of the links (MRUTHYUNJAYA, 2003). Thus, a kinematic structure has its kinematic chain and types of pairs defined.

A *point of interest* is a point in a mechanism's link which motion is relevant for the purpose of the device. A manipulator or an end-effector (such as a tool) can be placed at such point. This point's kinematic is analysed since it will interact with other bodies to execute the desired task. For example, in a packing mechanism the point of interest is the protrusion that pushes the object into the package (HARTENBERG; DENAVIT, 1964, p. 48).

Kinematic pairs can be modelled through screws. Briefly, the *screw system* is a base of the space to which all screws of the kinematic chain belong. Thus, the screw-system is composed of linearly independent screws that can be used to describe all other screws in the space. The order of the screw system, λ, is determined by the number of screws in the screw system's base. More details about this extensive topic are available in Hunt (1978), Tischler, Samuel and Hunt (1995) and Tischler, Samuel and Hunt (1995).

The *mobility*, M, of a kinematic chain is the independent number of variables that must be specified to completely define the positions of all kinematic chain's links (HUNT, 1978). Sometimes the mobility is also referred as the kinematic chain's DOF. The subchain's mobility in a kinematic chain is denoted M'.

The *connectivity*, C_{ij}, between links i and j is the relative mobility between them. Connectivity between two links can be determined by the lowest of the following three values: minimum quantity of single-freedom kinematic pairs between the two links; minimum value of M' considering subchains that contain both links; the order of the screw system, λ.

The degree of control, K_{ij}, between links i and j is the minimum number of independent actuated pairs needed to completely define the position between those two links. The degree of control between two links can be determined by the lowest of the following two values: minimum quantity of single-freedom kinematic pairs between the two links; minimum value of M' considering subchains that contain both links.

The values of connectivity and degree of control between two links can vary. The difference between the degree of control and the connectivity is called *redundancy*, R_{ij}. For more details about connectivity, degree of control and redundancy see Hunt (1978), Belfiore and Benedetto (2000) and Carboni and Martins (2007).

The *variety*, V, of a chain is the maximum value for the difference $M - M'$. Thus, when placing the actuators at a chain with variety two, the last two actuators must be placed carefully to avoid conflict among actuators. More details about variety can be seen in Martins and Carboni (2008) and Tischler, Samuel and Hunt (1995).

Structural characteristics are properties related to kinematic chains, such as mobility, variety, connectivity, order of the screw system, number of loops and links. *Design characteristics* are features desirable or required for the device and are not necessarily related to structural characteristics. Examples of design requirements are easiness to operate, being compact, light, silent, easy to manufacture and low cost. While it is easier to evaluate a device by its structural characteristics, design characteristics might be subjective and non-measurable.

2.2 MECHANISM DESIGN METHODOLOGIES

The design of mechanisms depends on several factors, such as knowledge, experience, skills and creativity of the designer. Mechanism design methodologies approach to the topic from a systematic view, making it less dependent on the human factors. Among such methodologies are those by Hartenberg and Denavit (1964), Yan (1999) and Tsai (2000).

Since there are similarities among the methodologies, Sections 2.2.1, 2.2.2 and 2.2.3 will expose only concepts of the methodologies and not how each step is done. A deeper approach in each step is presented in Section 2.4, after a new methodology is proposed.

2.2.1 Hartenberg and Denavit's methodology

Hartenberg and Denavit (1964) identify three stages that are always present in mechanism design: type synthesis, number synthesis and dimensional synthesis. These steps can interrelate and they appear in third party mechanism design methodologies, sometimes they are combined or with a different name or using additional mathematical tools such as graphs.

In type synthesis the types of kinematic pairs is decided . As examples of types of kinematic pairs we can cite revolute, prismatic, cam and gear.

According to Hartenberg and Denavit (1964), when choosing the type of kinematic pairs the designer must consider not only its kinematics. External factors, such as available materials, manufacturing process and the mechanism application, must also be considered. As type synthesis involves combinations, assigning different types among different kinematic pairs, the number of possibilities grows fast. Those external factors are used to reduce the number of available types of kinematic pairs.

The number synthesis has as goal to determine all possible kinematic chains that satisfy the design requirements. On this step it is defined the quantity of kinematic pairs and links, the partitions, all kinematic chains for each partition and all mechanisms for each kinematic chain. Tools for the kinematic chains enumeration will be presented in Section 2.4.2.2.

In dimensional synthesis the links' size and the points of interest's positions are determined. That involves also calculating the points of interest's positions to accomplish the design requirements. Besides, it may be necessary for the points of interest to satisfy not only the position but also the requirements for path, trajectory and angles.

Although the steps presented by Hartenberg and Denavit (1964) are important and appear in third party methodologies, their focus on the cited work was approximated dimensional synthesis. As they presented no tool or method for type synthesis and number synthesis, the cited work is more of an introduction to mechanism synthesis than a methodology. Therefore, besides its great contribution to mechanisms design, it is not possible to use only this methodology.

2.2.2 Yan's methodology

Yan (1999) proposes a methodology based on the graph representation of kinematic chains associated with permutation groups concepts. In this methodology, the structural characteristics are determined by a state of the art survey. Then, through number synthesis, all kinematic chains, which properties are similar to those found in the survey, are generated.

The methodology can be summarised in the following steps:

1. to make a state of the art survey considering the designs that satisfy the design requirements. To identify the structural characteristics;

2. to generalise the existing mechanisms, expanding their joints into revolute joints;

3. to generate the atlas of generalised chains. These chains must contain the same number of links and kinematic pairs than in those in the existing design. Graphs are used to make the number synthesis. Concepts of group theory are applied to avoid isomorphisms;

4. to generate the atlas of feasible specialised chains. In this process, the

types for kinematic pairs are chosen ; therefore, it is equivalent to type synthesis. Type synthesis is done using concepts of permutation groups to avoid isomorphisms. The specialised chain that satisfies the design requirements is denominated feasible specialised chain;

5. to particularise each feasible specialised chain to make the atlas designs. In this step, the links' size are determined; thus, it is equivalent to dimensional synthesis;

6. to separate the new designs from the atlas of devices to obtain the atlas of new designs.

The diagram of the methodology is exposed in Figure 10. The input data for number synthesis are the quantities of links and kinematic pairs. Therefore, the methodology does not depend directly on the screw system's order and the number of loops. Hence, discussions about the screw system's order and the number of loops are avoided.

The screw system's order and its type are determined by the necessary motion to complete the desired task. For example, a mechanism for orientation is a second special three-system with $h_y = 0$, see Hunt (1978) Section 12.7.2.

It is noted that selecting the type of the screw systems restricts the types of kinematic pairs that can be chosen, *e.g.*, if the screw system is a planar system, then cylindrical kinematic pairs cannot be used.

Therefore, the screw system is chosen by the points of interest's motions (considering the mechanism itself as a black box). It is possible to determine this mechanism, but, depending on the motion complexity, it might be only possible to do so with high numbers of loops and mobilities. Thus, although the choice of the screw system may appear straightforward, it has strong implications in the designing process; hence, it must be done carefully. A deeper approach to screw systems and its selection was done by Hunt (1978), Davidson and Hunt (2004) and Tsai (2000).

The higher the number of loops, more complex is the kinematic chain. Thus, it is desirable that it be as lowest as possible (TISCHLER, 1995).

Usually, in the synthesis process, it is hard to define the number of loops. Hence, several kinematic chains are generated with different number of loops. Starting by the lowest number of loops, these chains are analysed to see if they can successfully satisfy the design requirements. If they do not, then chains with higher number of loops have to be analysed.

As the methodology proposed by Yan (1999) avoids the direct determination of the screw system and the number of loops, it is a more straightforward methodology, being this an advantage of this methodology.

However, when the screw system or the number of loops is known, this methodology does not support them. Thus, in those cases the methodology presents a disadvantage since it is not possible to use the screw system or the number of loops as input.

The number synthesis process is a combinatorial process, hence, it is expected that it generates many results. The same occurs with type synthesis. Therefore, it is important to eliminate every kinematic chain that does not satisfy the design requirements or that is duplicated, *i.e.*, it was already generated.

This methodology foresees the use of permutation groups in number synthesis and type synthesis to avoid generating isomorphisms. More details will be exposed in Section 2.4.2 (number synthesis section).

One methodology limitation is that it uses the state of the art survey to determine the design requirements. Thus, it is limited by the already existing devices.

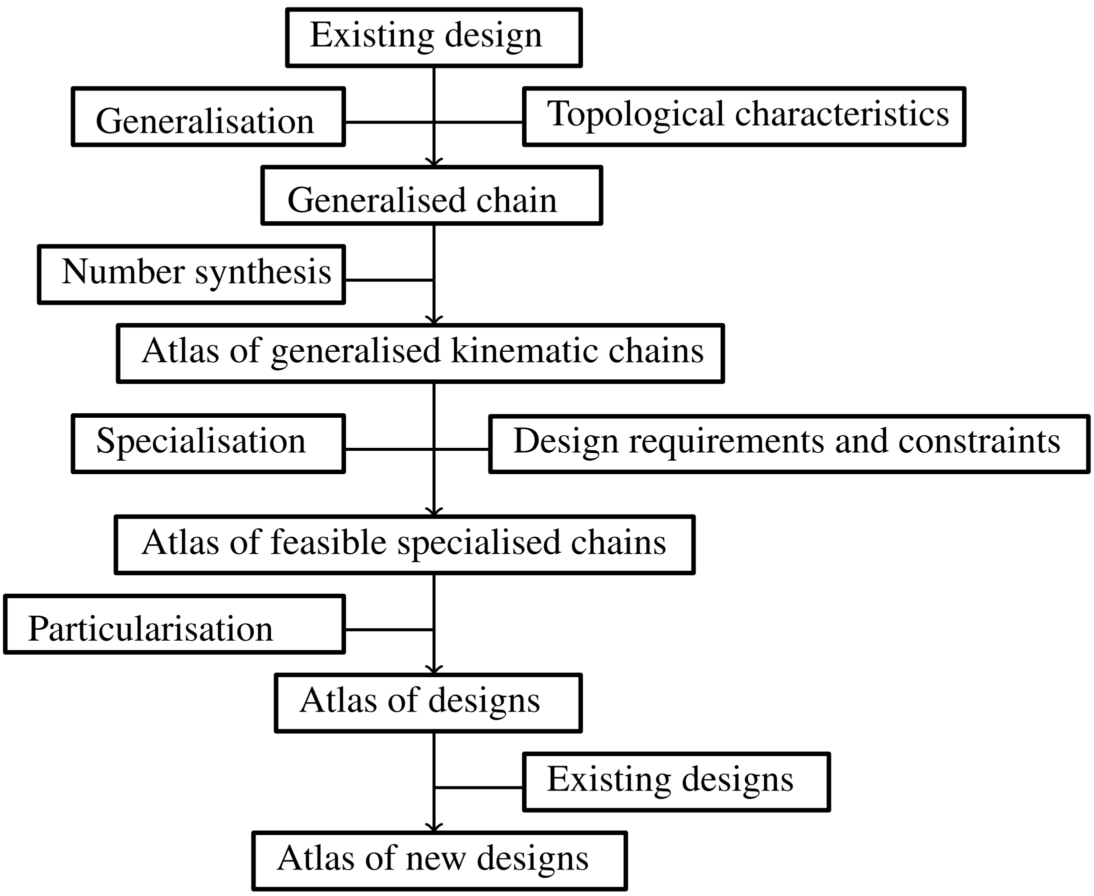


Figure 10: Methodology proposed by Yan (1999).

2.2.3 Tsai's methodology

The methodology proposed by Tsai (2000) is similar to Yan's methodology. Despite the fact that both are based on the graphs and permutation groups, in Tsai (2000) the structural characteristics are not restricted to a state of the art survey. Furthermore, Tsai (2000) considers two engines for the methodology, a generator and an evaluator, working in an iterative process.

The generator creates kinematic chains based on part of the design requirements. The remaining requirements are used in the evaluator to analyse the kinematic chains. It is up to the designer to define what requirements will be included in the generator. It might be complex to include many requirements into the generator, but it will reduce the work of the evaluator (TSAI, 2000).

The methodology can be summarised in the following steps:

1. to list the customer functional requirements;
2. to determine the structural characteristics;
3. to transform some functional requirements into structural characteristics in order to insert them in the generator;
4. to generate the kinematic structures using the structural characteristics as input data. This step includes the number and type syntheses. The enumeration is done using graph theory and combinatorial analysis;
5. to generate the mechanisms and evaluate them using the remaining design requirements;
6. to choose the most promising mechanism to make the dimensional synthesis, design optimisation, computer simulation, prototype and documentation;
7. production phase.

The diagram of this methodology is exposed in Figure 11. The major advantages of Tsai's methodology over Yan's methodology is the establishment of the design requirements and the iterative process of the generator and the evaluator.

As exposed in Section 2.2.2, the structural characteristics establishment may be complex. Although, once they are well-defined, it will not be necessary to variate the input parameters; thus, the process of synthesis will generate fewer kinematic chains. Also, with fewer chains, the analysis step will be faster and the generated kinematic chains will be more promising. Hence, the possibility of direct input of structural characteristics is an advantage of Tsai's methodology.

During the design process, the iteration involving the generator and evaluator continues until all feasible mechanisms are created and separated from the non-feasible ones. It notices that in Yan's methodology there is no iteration, therefore, the analysis done in step four of the cited methodology functions as a filter for non-feasible kinematic chains. In the methodology proposed by Tsai (2000) the iterative process can function as an optimisation process. In this case, the evaluator would modify some generator's input data to increase the number of feasible kinematic chains as well as their quality (more promising chains).

When the choice of some structural characteristic is unclear, Tsai's methodology can generate kinematic structures using several values for it. For example, when the number of independent loops is unknown, the synthesis process can be done adopting a range of values for it.

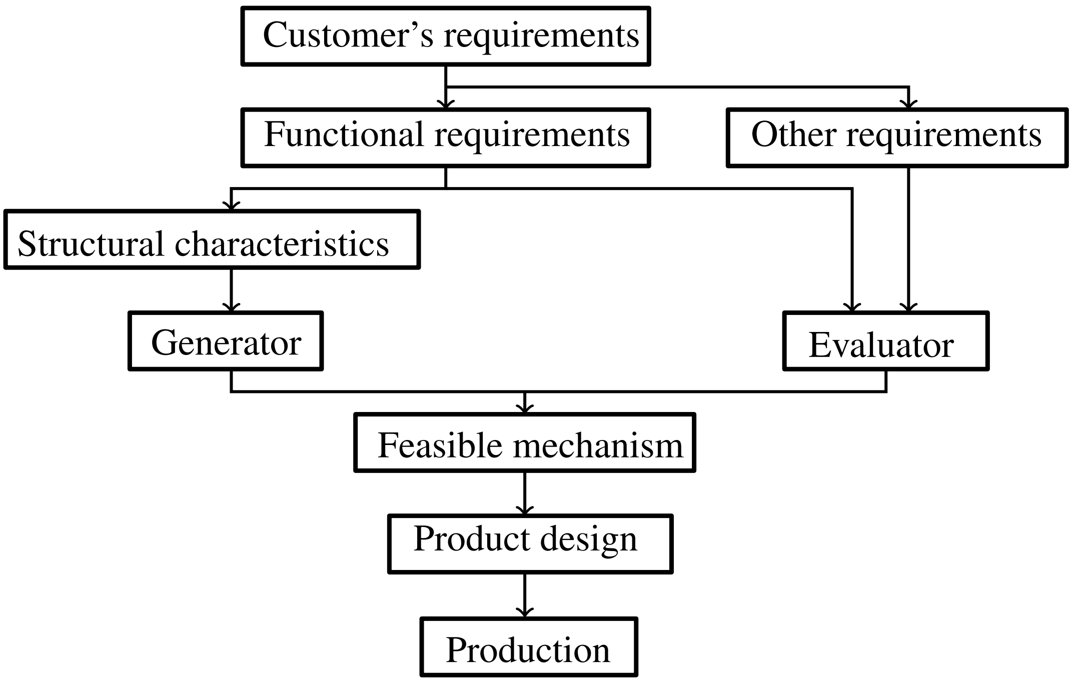


Figure 11: Methodology proposed by Tsai (2000).

2.3 PROPOSED METHODOLOGY

The proposed methodology combines some aspects of the methodologies presented in Section 2.2.

As in the methodology proposed by Yan (1999) (Section 2.2.2), a state of the art survey is done. A goal for this step is to list existing devices that satisfy the design requirements. A better understanding of the subject from the designer and also to guide the designer through the project decisions are among the state of the art survey objectives.

While making the state of the art survey, the designer must analyse a few aspects of the existing devices, such as their screw system, mobility, number of independent loops and other design and structural characteristics, as will be exposed in this section.

Once the survey is done, the designer will be able to determine the screw system, mobility and a few possible values for the number of independent loops. When the structural and design requirements are chosen, it is possible to make number and type syntheses.

The following sections will expose how the structural characteristics can be determined with little or no dependency on the designer.

2.3.1 Considerations about the screw system

Once the survey is done, for each of its devices, the points of interest relative motions are analysed. Based on this analysis, the screw system is determined. When the device has only one point of interest, the motion of this point relative to the fixed link is analysed . These analyses consider only the cited links moving in space, but performing the motions as in the complete mechanism. This abstraction makes easier to identify the screw system, since it separates the focus of the analysis from the rest.

This method is also useful when the mechanism in analysis presents subchains with different screw systems or even when the screw system's orders are different. As the chains, the changes in the screw systems are no longer visible, the analysis is more impartial, focusing only on the main motions.

When the task is not well-defined, the determination of the screw system is an engineering choice. This choice can be guided analysing the devices of the survey. For example, a multi-purpose robot arm can do several tasks, as welding, measuring, pick-and-place and assembling. These tasks will not always use the six-system, but any other screw system would impose undesirable limits, thus, the most of the multi-purpose robot arms work in six-system.

2.3.2 Considerations about the mobility

The mobility for the device is usually known. It can be determined analysing the desired motions and how they can change. For instance, when the device always repeats a specific motion, its mechanism will probably have mobility one. However, if the motion must change according to a configuration parameter, then the mechanism will have more than one mobility. The determination of the mobility can be guided analysing the survey's devices.

In robotics, an important step is to analyse the need for redundancy. Since redundancy allows the manipulator to execute the same task in different configurations, it can be used to avoid or escape from singularities. In addition, redundancy is useful in confined spaces to increase the workspace and avoid collisions (SIMAS, 2008; SIMAS et al., 2009; SIMAS; MARTINS; GUENTHER, 2003). Redundancies must be added to the device mobility.

2.3.3 Considerations about the number of independent loops

The screw system is defined analysing the points of interest necessary motions, thus, these points and their links are already in the screw system. The kinematic chain must not only lie in the screw system, but also be capable of following the desired motion for the points of interest. Thus, the complexity of the kinematic chain depends on the complexity of the desired motion.

The survey can also help to determine the number of loops (or at least to restrict it to a few possibilities); even though, the number of loops is not always well defined for the synthesis process. In this case, synthesis can be done by selecting a low value for the number of loops and verifying if the resulting mechanisms are capable of executing the desired motion. If not, the the number of loops is increased and the process repeats. The choice for the number of loops is an engineering decision and can be guided by the survey.

2.3.4 Considerations about other design characteristics

Others structural and design characteristics may be noticed on this survey. It is important to take notes of them because they will be used in the synthesis and analysis process. But, unlike Yan's methodology, the survey is used only as guidelines; therefore, the structural parameters used in the synthesis process not necessarily have to be equal to those found in the survey. Thus, when some structural characteristics are not defined, the synthesis process can be done for a few well-chosen value for them. This is an important feature of the proposed methodology.

Yan's methodology seeks for innovation by synthesising all mechanisms which structural characteristics are the same as those which were found on the survey. This makes the determination of the structural requirements more straightforward; however, it also limits the space of solutions to a group of structural requirements. Creative solutions can appear by making the synthesis using different structural requirements from those which were found in the survey. Hence, to understand better the problem itself and not only the solutions for it is another goal for the survey.

2.3.5 Considerations about the generator and the evaluator

As in the methodology proposed by Tsai (2000), a generator and a evaluator are done. Three structural characteristics are used in the generator to enumerate the mechanisms. Any method for the enumeration can be used and this choice must consider several factors, as the familiarity of the designer with the method, easiness to implement or if it is already implemented and if it is necessary to optimise the enumeration process. The enumeration technique choice is up to the designer.

The evaluator must exclude improper mechanisms. Structural and design characteristics from the survey are used in the evaluator to compose the filters. Thus, the survey must be as complete as possible, examining both the problem and existing solutions. While doing the analysis of the survey, desirable design characteristics will be noticed. Besides these characteristics, the designer must also search for other desirable features that did not appear in the survey. These new incoming characteristics are important because they have a great potential for innovation. In the search for this features, the designer must consider not only how the device will work, but also the best ways to operate, maintain, assemble, disassemble and manufacture it. By analysing all the interaction that the device could have with humans or machines, new desirable design characteristics may appear.

The evaluator will reduce the number of mechanisms, thus, helping the designer in the task of selecting one or a group of mechanisms to continue the synthesis process. Since the generator and the evaluator work in a cycle, when no mechanism is feasible, the generator's input data must be changed accordingly and a new enumeration is done, in order to search for feasible mechanisms. An example of selecting kinematic chains for a specific task is given in Tischler, Samuel and Hunt (2001).

2.3.6 Type synthesis and further steps

As the next steps are time-consuming, it is desirable to select the most promising mechanism to continue the synthesis process. Although, the designer might select a few mechanisms to postpone this decision, waiting for the mechanisms to be more developed. After a mechanism or a group is selected, type synthesis is done. Structural and design requirements are used to select types of kinematic pairs and to allocate them in the pairs. More details of type synthesis will be exposed in Section 2.4.3.

Once the pairs type is defined, dimensional synthesis and design optimisation are done. Computer simulations in a computer-aided design (CAD) software and prototypes are made. If necessary, adjustments are done. These adjustments may be done in dimension, joints, types of pairs, materials and manufacturing process. An example of joint adjustment would be a change from journal bearing to rolling contact bearing. An example of type of pair adjustment would be a change from prismatic to revolute pair, or, from revolute to spheric to apply self-aligning concepts.

Then, patent process and other documentations are done. Finally, the device enters in production.

2.3.7 Summary of the proposed methodology

The methodology can be summarised in the following steps:

1. to make a state of the art survey. To consider designs that satisfy the design requirements or execute similar functions. Customer requirements must also be listed;

2. to identify the design and structural characteristics of the devices and mechanisms of the survey;

3. to determine the structural and design requirements for the project based on the characteristics of the survey;

4. to select three structural characteristics from the requirements and use them as input in the generator;

5. to generate all possible mechanisms;

6. to evaluate the mechanisms and eliminate the unfeasible ones. If no mechanism is feasible, to change the structural characteristics and insert them in the generator;

7. to select the type of each kinematic pair once a feasible mechanism or a few feasible mechanisms are chosen. Structural and design characteristics are used to guide the designer in this step;

8. to do the dimensional synthesis. Dimensions must allow to the mechanism to perform the motions according to the design requirements. A CAD software along with optimisation routines can be used to assist the designer in this step;

9. to make the prototype. If further adjusts are required, type or dimensional syntheses can be done again;

10. to do the documentation once the prototype satisfies the design requirements;

11. to manufacture the device.

A diagram of the proposed methodology is exposed in Figure 12.

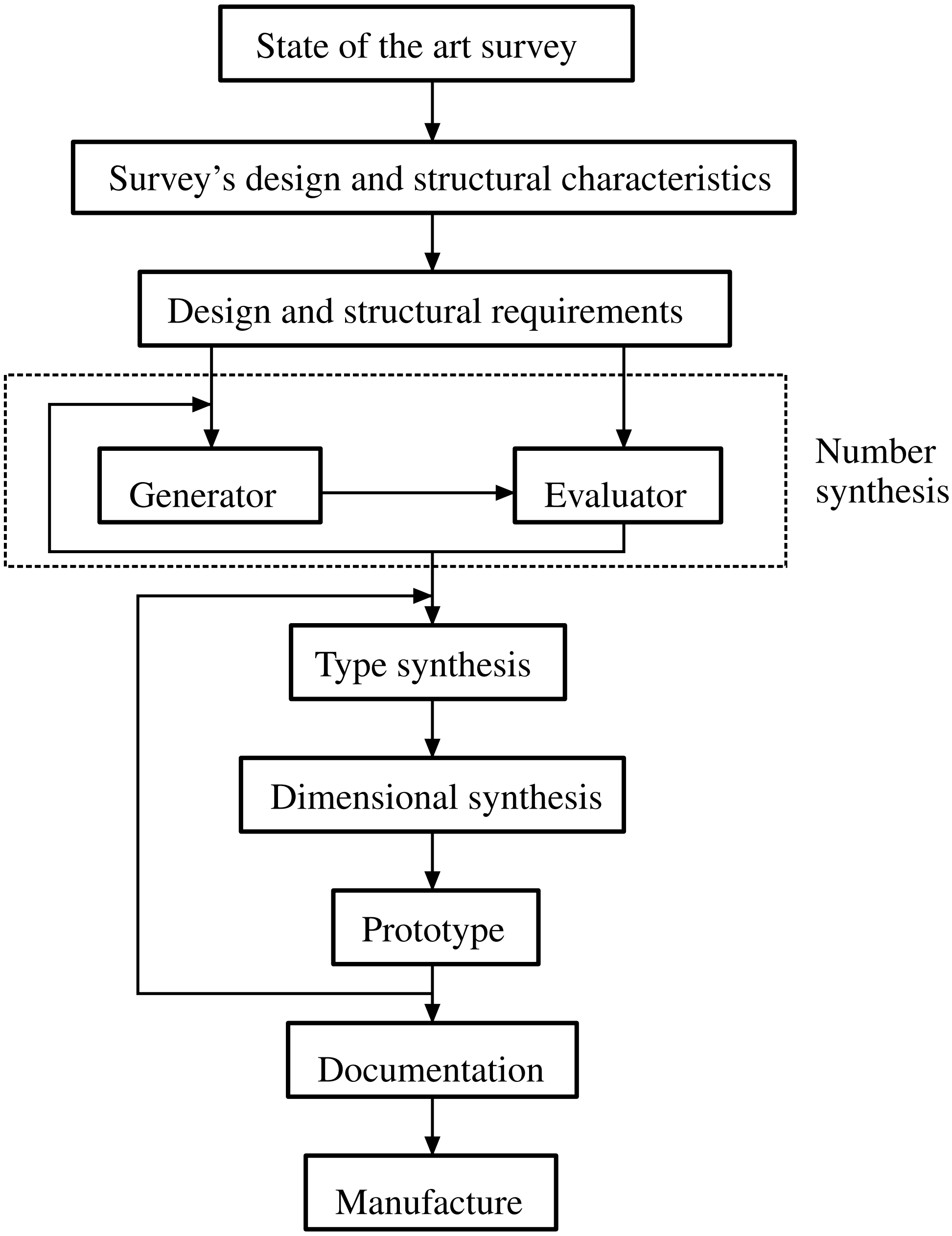


Figure 12: Proposed methodology.

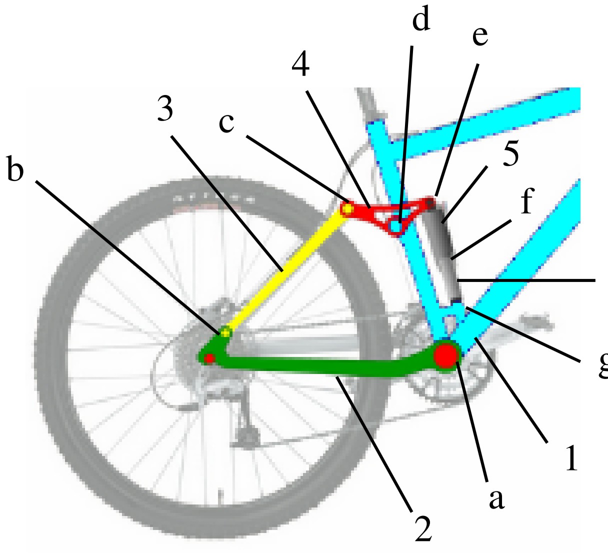
2.4 THEORETICAL TOOLS

2.4.1 Representations of kinematic chains

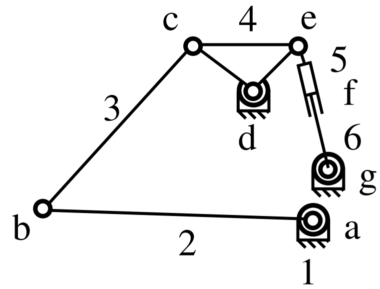
A kinematic chain may be represented by three different ways: functional, structural and graph representations.

Functional representation is a cross-section view of the mechanism. This schematic depicts the joints as the motions allowed by the kinematic pair. Mechanical elements, such as gears and pulleys, are represented as they are.

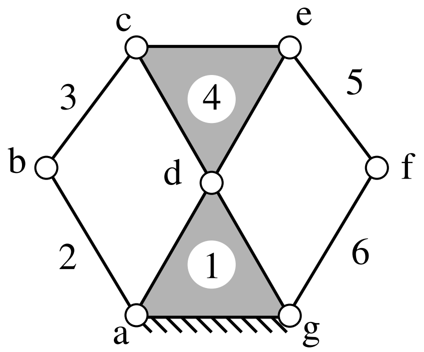
However, in this representation only the necessary components are shown, in order to make the visualisation clearer. Functional representational is more understandable and intuitive if compared to structural and graph representation. Figure 13a exposes a mountain bike suspension and its links and joints labels. The functional representation of this suspension is shown in Figure 13b.



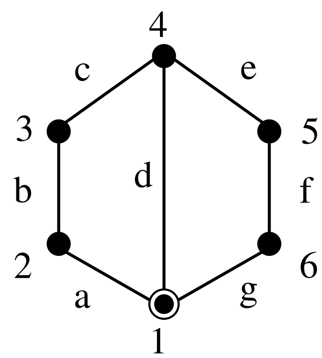
(a) Mountain bike suspension. Adapted from Cartemere (2008).



(b) Functional representation.



(c) Structural representation.



(d) Graph representation.

Figure 13: Representations of a kinematic chain.

The structural representation shows the types of links (binary, ternary, and so on) and which links are connected. Polygonal links are represented by filled polygons and binary links are represented by simple lines. All kinematic pairs are expanded to pairs with one DOF. In structural representation, dimensions and angles are not preserved. Therefore, structural representation is not so intuitive as it is functional, but it exposes better the connectivity among the links. The structural representation of the suspension is shown in Figure 13c.

The graph representation depicts links as vertices and kinematic pairs as edges. Therefore, two links connected by a pair are represented as two vertices connected by the respective edge. As in kinematic chains, edges and links can be distinguished by their labels. Although graph representation is the least intuitive of the presented representations, it has some advantages. A kinematic chain can be represented in a biunivocal way by a graph, *i.e.*, a graph represents only one chain and a chain is represented by only a graph. When representing chains with graphs, properties from graph theory can be applied to kinematic chains. Another great advantage is its easiness to develop and to implement algorithms. Therefore, graph representation is used in both synthesis and analysis. Enumeration of kinematic chains, mechanisms and manipulators can be done by enumerating their respective graphs (SIMONI; MARTINS, 2007; SIMONI; CARBONI; MARTINS, 2009b); and the analysis of the properties of a chain can be done by analysing the properties of its graph (CARBONI; MARTINS, 2007; MARTINS; CARBONI, 2008). An example of a kinematic chain and its representation using a graph is shown in Figure 13d.

2.4.2 Number synthesis

This section's objective is to introduce the concepts of each number synthesis' step and to show how design and structural characteristics can be used to help in the designer's decisions. Through this section, the same example will be used, although it will not be fully developed with all its kinematic chains and mechanisms. More tools and techniques for enumeration of kinematic chains and mechanisms are shown in Simoni, Carboni and Martins (2009a), Simoni and Martins (2007), Simoni (2010), Tischler (1995), Tischler, Samuel and Hunt (1995), Sunkari and Schmidt (2006), Mruthyunjaya (2003); and the current status of kinematic chains enumeration is shown in Simoni et al. (2011).

According to Hartenberg and Denavit (1964), number synthesis is the study about how the quantity of kinematic pairs and links will influence the mobility of the kinematic chain. This mobility can be determined through the Grübler equation,

$$M = (n-1-j)\lambda + j, \tag{2.1}$$

in which n is the quantity of links, j is the quantity of kinematic pairs with one DOF and λ is the screw system order.

Equation 2.1 yields the mobility of a mechanism according to its structural characteristics. However, the mobility also depends on other factors, such as links' dimensions and positions. Therefore, in some cases, Equation 2.1 fails to give the correct mobility. Nevertheless, dimension is not known in the syntheses initial phase; thus, Equation 2.1 can be used as long as the designer keeps in mind its limitations. For more details on mobility see Gogu (2005).

The use of Euler's equation is often needed,

$$\nu = j - n + 1, \tag{2.2}$$

in which ν is the number of independent loops of the kinematic chain. Once the number of kinematic pairs is determined, the elements of kinematic pairs quantity (e) is $2j$.

Example 1 *Consider the number synthesis of a planar kinematic chain ($\lambda =$ 3) with mobility two ($M = 2$) and three independent loops ($\nu = 3$). Using Equations 2.1 and 2.2, the number of elements of kinematic pairs and links are:*

$$j = 11 \longrightarrow e = 2j = 22$$

$$n = 9.$$

Number synthesis is a combinatorial problem, which results are often too large (TISCHLER; SAMUEL; HUNT, 2001). Therefore, when a partition, kinematic chain, or mechanism leads to an unfeasible solution, they should be excluded from the synthesis process, as soon as possible, to reduce the designer's effort and also the time spent in the execution of the computational synthesis and analysis. There are two approaches to deal with unfeasible solutions. The undesired results might be eliminated during the enumeration process, avoiding to generate them in the first place, or, after the enumeration, excluding them after the respective step of the synthesis is done. The former approach increases the implementation costs, whereas, the latter increases the computational costs. Thus, choosing which approach will be adopted is ultimately an engineering decision.

As cited in Section 2.3.5, the characteristics that make some result be unfeasible can be implemented in the generator, thus, it will generate less mechanisms but more promising ones. However, these characteristics can also be implemented in the evaluator, filtering results after they are generated.

Finally, the number of results must be considered. The designer must analyse the input data and estimate the number of results. If possible, the designer can choose to make the number synthesis manually. This can be used to avoid the implementation costs or to check the results from the computational enumeration.

2.4.2.1 Establishing the partitions

The elements of kinematic pairs can be distributed among the links in various ways, resulting in different partitions. Considering the synthesis of parallel kinematic chains, each one of the n links must have at least two elements of kinematic pair. The remaining $2(j-n)$ elements must be assorted to obtain the partitions, as shown in Example 2. For the synthesis of hybrid kinematic chains, the assortment must result in partitions, in which the number of unary links is equal to the number of desired serial chains.

Example 2 *Referring to Example 1, after the distribution of two elements for each one of the nine links, four elements remain. These elements can be assorted in five different ways, generating the five partitions shown in Table 1. Such partitions are obtained by the following assortment:*

- *one link receiving all elements;*
- *one link receives three elements and the other link receives the remaining elements; or two links getting two elements each;*
- *three links, with one link receiving two elements and two links receiving one element;*
- *four links, each one receiving one element.*

Table 1: Partitions of the parallel planar kinematic chain with $M = 2$ and $\nu = 3$. Polygonal links are greyed out.

Partition	Link								
	1	2	3	4	5	6	7	8	9
1	6	2	2	2	2	2	2	2	2
2	5	3	2	2	2	2	2	2	2
3	4	4	2	2	2	2	2	2	2
4	4	3	3	2	2	2	2	2	2
5	3	3	3	3	2	2	2	2	2

However, some partitions might not be interesting, therefore, they should be excluded from the synthesis process. For example, if it is known that the fixed link must have four kinematic pairs, then all partitions that do not contain a quaternary link can be eliminated. If fractioned kinematic chains (Section 2.4.2.2) are not desired, then partitions that have only one polygonal link can be discarded, as well as those with two polygonal links with different quantity of elements.

2.4.2.2 Establishing the kinematic chains

In a partition, the links can be assembled in several ways, resulting in different variations (or kinematic chains). For each partition, all kinematic chains are enumerated. There are several methods of kinematic chains enumeration, as exposed by Simoni and Martins (2007) and Simoni et al. (2011). Every method has its own characteristics, some are based on graph theory, others on Frank's notation, or on Assur groups. There are also methods that generate only fractionated kinematic chains (MARTINS; SIMONI; CARBONI, 2010), others that avoid to generate fractionated chains (SIMONI; CARBONI; MARTINS, 2009a) or isomorphic chains.

This section will briefly expose only Farrell's method for didactic reasons, although, as cited in Section 2.3, the choice of the method is up to the designer.

Farrell's uses a tree structure to build all possible graphs within a given partition.

First the partition is sorted by the vertices degree, from the highest to the lowest. The vertex with the highest degree is adopted as the initial vertex.

All possible graphs that can be done by inserting one vertex are determined. Notice that such graphs are generated considering the degree of the vertices. Thus, when an element of the binary group has already been used to generate a branch, the method will not use another element of the same group to generate an isomorphic branch.

Figure 14 shows an example of Farrell's method using partition three of Example 2. Notice that there are two non-isomorphic possible branches, the first is connecting a vertex from IV and three from II, the second is connecting all vertices from II.

Furthermore, in the first iteration, the method is straightforward. However, in the next interactions, connecting two pending ends of the graph must be considered. More details of Farrell's method in Farrell (1977) and Simoni and Martins (2007).

The enumeration process will generate all possible kinematic chains, the more and the less promising ones. Thus, it might be desirable to exclude kinematic chains with specific characteristics, such as degenerated and iso-

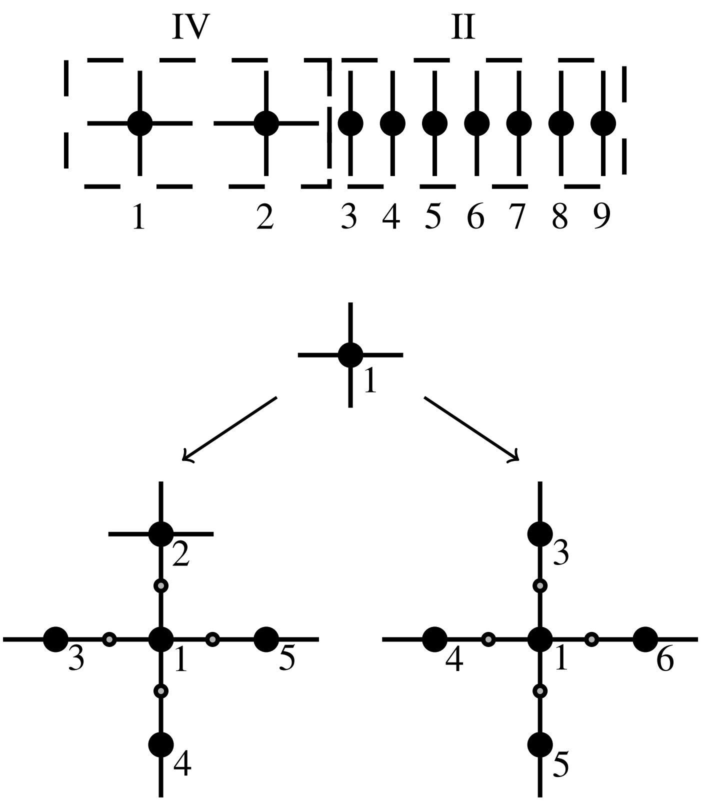


Figure 14: Example of Farrell's method.

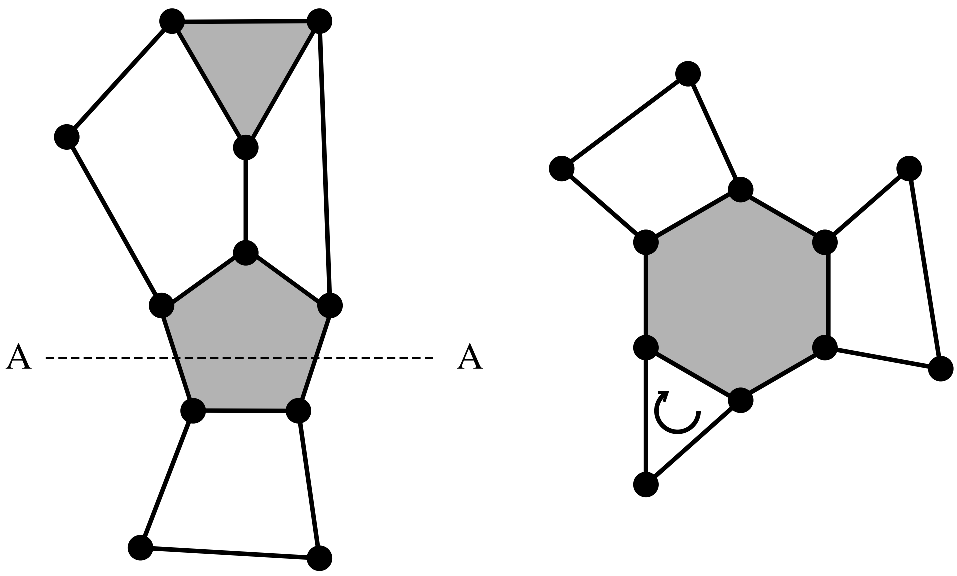
morphic chains.

Degenerated kinematic chains are divided in two categories: fractioned and improper chains.

Fractionation in kinematic chains can be classified in three types:

- *body-fractionated* occurs when it is possible to cut a link and the result are two closed separated kinematic chains;
- *joint-fractionated* occurs when the disassembly and elimination of a kinematic pair results in two closed separated kinematic chains;
- *fractionation into hybrid kinematic chains* occurs when both previous fractionations appear together in the same kinematic chain.

A fractionation shows that the kinematic chain is not a new solution, but the combination of other kinematic chains. In addition, fractionated kinematic chains restrict the choice for the actuated joints, *i.e.*, fractionated chains have variety greater than or equal to one. Therefore, these less promising chains are sometimes discarded. Figure 15a shows a body-fractioned kinematic chains generated from partition 2 of Example 2. It notices that when the quinary link is cut as indicated by line A-A, the result are two independent and closed kinematic chains. The upper chain is a Stephenson chain and the lower is a four-bar linkage.



(a) Body- fractionation. (b) Baranov subchain.

Figure 15: Example fractionation and Baranov subchain.

The designer must eliminate or be careful when using fractionated chains if the synthesis problem does not have flexibility on the placement of the actuators. For example, in some applications it is desired that all actuators be placed on the fixed link. This reduces the weight and simplifies the project. In this case, using a body-fractioned chain would imply that the fixed link must be the fractioned link. This limitation will reduce the number of solutions or totally eliminate them. Thus, it might be desirable to do not generate fractioned kinematic chains. Although the choice of elimination fractionated chains relies on the designer and, therefore, fractionation is not always considered a degeneration. A deeper analysis of the fractionation problem was made by Martins, Simoni and Carboni (2010).

Improper kinematic chains are chains that contain a biconnected subchain which mobility, M', is non-positive. When the mobility of the subchain is null, the subchain is called a Baranov truss or Baranov subchain.

These subchains with non-positive mobility can be considered a structure and its properties differ from the calculated ones. Therefore, improper chains are not always desired and must be eliminated from the synthesis process.

In Figure 15b, the indicated subchain is a Baranov subchain (kinematic chain generated from partition 1 of Example 2). Therefore, this subchain can be replaced by a structure, resulting in a kinematic chain with a quaternary link and two four-bar linkages. Carboni (2008) makes a deeper approach on Baranov trusses.

Isomorphic kinematic chains have the same structural and topological characteristics. The difference among those chains relies on the names of the links and kinematic pairs.

Figure 16 shows an example of how isomorphisms occur during the number synthesis of partition 5 of Example 2 using Farrell's method.

Since these chains are duplicated, generating them and continuing the synthesis process with them is undesirable. Thus, isomorphic kinematic chains must be eliminated from the synthesis process. More details about isomorphism and methods on how to avoid it can be found in Sunkari and Schmidt (2006), Simoni and Martins (2007) and Simoni, Carboni and Martins (2009a).

Variety can also be used to eliminate kinematic chains, although, as fractionation, this must be done carefully. The higher the variety, the less flexible is the choice for the placement of the actuators. Thus, it is desirable to have kinematic chains with a low or zero variety.

Unlike Baranov subchains and isomorphism, fractionation and variety are not always exclude-only properties. The designer must know the effect of these properties on kinematic chains and made a proper use of them to exclude or to choose chains. A deeper approach on the variety property is done by Tischler, Samuel and Hunt (1995) and Martins and Carboni (2008).

Finally, design requirements can be used to eliminate unfeasible chains. For example, when a planar application requires great forces from the actuators, hydraulic or pneumatic actuators can be used. These actuators are often composed by two links with a prismatic and two revolute pairs, as shown in Figure 17a. Therefore, the kinematic chain's structure must have two binary links connected (dyad), as shown in Figure 17b. In this example, the design requirements dictated the type synthesis and it imposed that condition over kinematic chains.

The device application, what kinds of joints are easy to manufacture and actuate and how it is going to be actuated, are examples of design requirements that can be used to eliminate unfeasible chains. It is up to the designer to notice these and other characteristics.

2.4.2.3 Establishing the mechanisms

Once all kinematic chains are enumerated and all the undesired ones eliminated, for each remaining chain a link must be chosen to be the fixed link, resulting in different inversions (or mechanisms). As each chain can

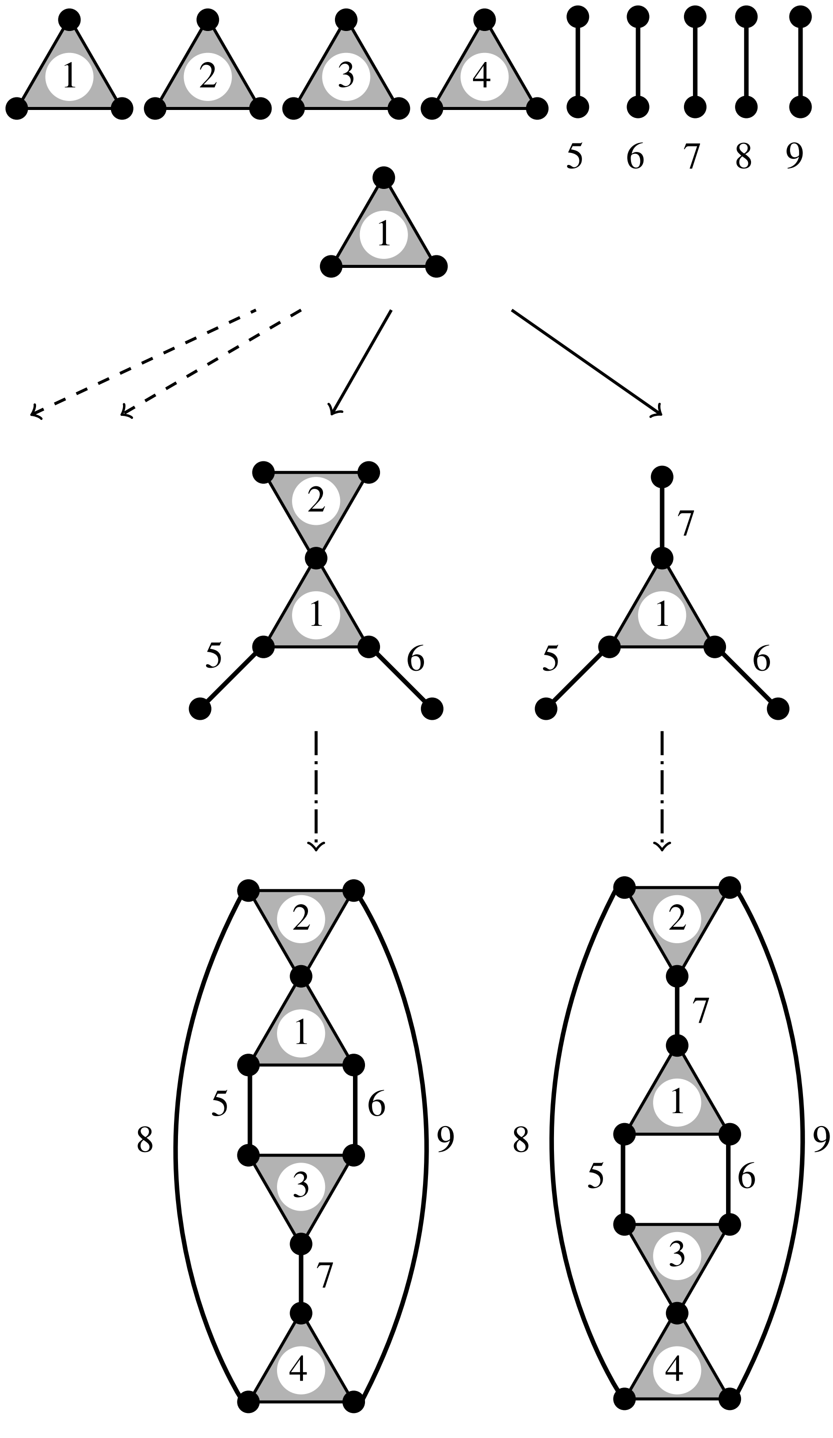
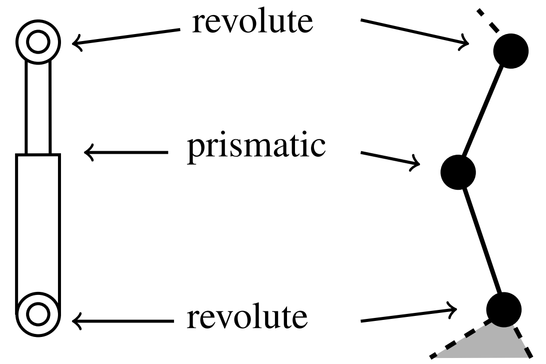


Figure 16: Example of formation of isomorphic kinematic chains.



(a) Actuator. (b) Kinematic chain.

Figure 17: Example of an actuator and its kinematic chain.

generate up to n mechanisms, the results are often large. Thus, it is desirable to exclude mechanisms that are isomorphic or do not have some specific characteristic.

For example, if it is required that the actuators be placed on the fixed link, then the chosen link must have at least M kinematic pairs. Furthermore, the fixed link must accept all actuators properly, *i.e.*, without the actuators conflicting among themselves. When no polygonal link with such properties exists in the chain, the chain can be discarded (it notices how variety property is important).

2.4.2.4 Establishing the position of the points of interest and the actuators

For each feasible mechanism, the links that will contain the points of interest are chosen. These links must be chosen considering the desired motion for the points of interest; thus, the connectivity among the cited links and the fixed link must allow the points of interest to execute the desired motions.

Then, for each mechanism with the points of interest's links defined, all possible ways of distributing the actuators must be generated and analysed. During this step, structural characteristics can be used to identify the feasible results, such as the subchain mobility and the mechanism variety. For example, when a mechanism has variety one, the last actuators must be placed carefully so it will not conflict with the previously placed actuators. If two actuators conflict with each other, *i.e.*, they are both placed on a subchain with mobility one, then the mechanism is unfeasible and it must be discarded.

It notices that the order of these two steps can be inverted, *i.e.*, the actuators placement can be done before the points of interest placement.

Also, these steps can influence in type synthesis. For example, when a point of interest must have a rotative motion in relation to the fixed link, the point can be placed at a link connected to the fixed link and the kinematic pair must be revolute. Considering the actuators placement, when the actuators are stepper motors, the kinematic pair that will have the actuators must be revolute. Therefore, the design requirements for the points of interest and the actuators can be used to identify the type synthesis feasible results.

Nevertheless, the points of interest and the actuators placement can also be done after type synthesis. In this case, type synthesis can influence the points of interest and actuators placement. For example, when it is desired that a point of interest executes a translational motion relative to the fixed link, such point cannot be placed in a link connected to the fixed link with a revolute pair. Considering the actuators placement, when a pair is revolute, the actuator placed on that pair must be a revolute motor. If no revolute motor is available, then such pair cannot hold an actuator or the mechanism will be unfeasible. Therefore, the type synthesis can reduce the number of feasible results when placing the points of interest and actuators.

The points of interest and the actuators placement can be done before or after type synthesis, *i.e.*, the placements can be done during number synthesis or type synthesis. Hence, in this work, such steps will appear in both number and type syntheses summary.

2.4.2.5 Number synthesis summary

The number synthesis can be summarised in these steps:

1. to determine the quantity of links and kinematic pairs with one DOF;

2. to determine the partitions;

3. to enumerate the kinematic chains for all partitions;

4. to enumerate the mechanisms for all kinematic chains;

5. to generate all feasible mechanisms with the points of interest placed (see last paragraph of Section 2.4.2.4);

6. to generate all feasible mechanisms with the actuators placed (see last paragraph of Section 2.4.2.4).

2.4.3 Type synthesis

As cited in Section 2.2.1, type synthesis determines the types of kinematic pairs.

First the design must choose what kind of kinematic pairs are available to be used. According to Hartenberg and Denavit (1964), available materials and manufacturing process influence this choice. Other factors that can be used to restrict the types of kinematic pairs were described in the end of Section 2.4.2.2. Costs must also be considered, for example, higher kinematic pairs are more complicated to manufacture and to maintain, therefore, more expensive. Further, while choosing the pairs or making a contraction, the pairs must be compatible with the screw system.

Once the possible types of kinematic pairs are determined, these types are associated to the chains' pairs in every possible way. As making all these combinations can be a laborious task, usually a computer is used. The result is often large, thus, design requirements can be used to eliminate chains with undesired characteristics. Example 3 shows how design requirements can be used to reduce the quantity of results.

As kinematic chains and mechanisms enumeration, type synthesis also generates isomorphisms. Yan (1999) uses concepts of group theory to eliminate isomorphic specialised chains (kinematic chains with defined type of pairs).

More recently, methodologies that combine number and type syntheses to design parallel mechanisms were developed. Kong and Gosselin (2007) use screw theory to generate all possible parallel mechanisms capable of executing a given motion. Li, Huang and Hervé (2004) use Lie groups theory to develop a method to enumerate all possible parallel mechanisms that satisfy a motion requirement. Gogu (2009) uses evolutionary morphology to generate parallel mechanisms that perform a given motion. Santos (2011) compares these three approaches for type synthesis and proposes a new method for type synthesis of parallel mechanisms, based on evolutionary morphology and on screw theory. As these methodologies comprise both number and type syntheses, it is not possible to directly apply them when the number synthesis is already done. However, it is up to the designer to choose which method or tool will be used to make the number and type syntheses.

Example 3 - ***Mechanism to separate a fixed amount of cement for packing***

Consider the problem of designing a mechanism to separate a certain amount of cement for packing. The mechanism must contain a recipient that will be filled with cement. Once the weight of the cement inside the recipient matches the required weight for packing, the recipient must incline and its *lateral wall will open.*

Consider the following design requirements of the project:

- *a hydraulic actuator is needed in order to support high loads;*
- *a revolute motor is needed to open the lateral wall;*
- *the actuators must be placed on the fixed link, except the hydraulic actuator;*
- *kinematic pairs must be either revolute or prismatic, for simplicity.*

For the sake of an example, let us choose the fourth partition of Example 2, shown in Figure 18a, to continue the synthesis. From this partition it is possible to build the mechanism exposed in Figure 18b. Initially, if just revolute and prismatic pairs is used, the quantity of solutions is 2048.

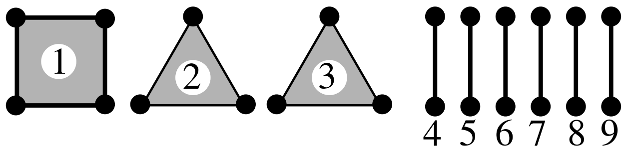
It notices in Figure 18b that it is possible to make a four-bar linkage with links 1, 2, 3 and 6. When the recipient is placed at link three, such four-bar linkage can be used to lift the recipient's high load. The hydraulic actuator must be placed properly to actuate the four-bar linkage. If it is placed on links four and five, all of its power can be used to sustain the recipient as well as to incline it.

The mobility of this mechanism is two, and the minimum subchain's mobility is one, thus, variety is one. Since the chain has variety one, the last actuator must be placed carefully. The revolute motor must be on the fixed link, thus, the only available choice is the kinematic pair connecting links one and seven. The result is the mechanism exposed in Figure 18c.

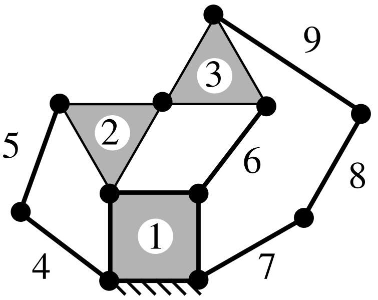
Another possibility for the hydraulic actuator were links seven and eight, however, this configurations are not desired, since the revolute pair's load would be greater than in the previously presented configuration.

Three pairs remain to be defined, pairs a, b and c in Figure 18c. These remaining pairs can be either revolute or prismatic joints, thus, 8 different combinations for type synthesis. The design requirements reduced from 2048 possibilities to only 8, which can be easily manually analysed by the designer.

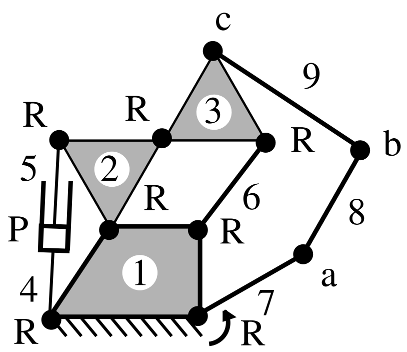
Additionally, after the pairs are defined, self-aligning concepts can be used. This technique provides devices that are capable of compensating small manufacture or assembly errors. Also, it makes the manufacture and maintenance of the device easier and cheaper. Self-aligning removes redundant restrictions, hence, it inserts more degrees of freedom. This extra freedom is used to position the links and joints, so the mechanism can be assembled. However, this freedom may exceed the screw system, thus, the mechanism can make undesirable motions.



(a) Partition.



(b) Kinematic chain.



(c) Chain with actuators.

Figure 18: Example of selection of driven kinematic pairs.

Using self-aligning will modify structural parameters, *i.e.*, the number of joints with one degree of freedom and the number of links will increase and the screw system may change. Although, as the extra-freedom acts in a short range, sometimes these structural modifications can be disregarded. For example, when a mechanism does not require much precision, its kinematic analysis can be approximated by disconsidering the self-alignment. Nevertheless, self-aligning must be done carefully. More details about self-aligning are available in Reshetov (1982), Szydlowski (2000), Carreto (2010) and Carboni, Simas and Martins (2012).

Type synthesis can be summarised in the following steps:

1. to determine the types of kinematic pairs available to use;

2. to generate all possible feasible combinations of mechanisms with the types of kinematic pairs already defined;

3. to generate all feasible mechanisms with the points of interest already placed (see last paragraph of Section 2.4.2.4);

4. to generate all feasible mechanisms with the actuators already placed (see last paragraph of Section 2.4.2.4);

5. to apply self-aligning concepts on the chosen feasible mechanisms.

2.5 CONCLUSIONS

In this chapter, basic concepts of mechanism were reviewed. Three mechanisms design methodologies were exposed, as well as their advantages and disadvantages. Based on the presented methodologies, a new methodology for mechanisms design was proposed. For each main step of the proposed methodology, tools were presented, focusing on how to use the design and structural requirements in order to aid in the selection of the most promising mechanisms.